Modelling the Soiling Rate: Dependencies on Meteorological Parameters

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Outline

- Introduction to soiling issue
- Measurements and sites used in this study
- Soiling model architecture, training and validation
- Results and performance of soiling model
- Summary and outlook

Soiling information on a global scale?

- There are several instruments for soiling measurement available
- Long term measurement of the soiling rate is time consuming, costly and **only for singular points** (within solar field or in resource assessment)
- Project developers require more global data for site selection

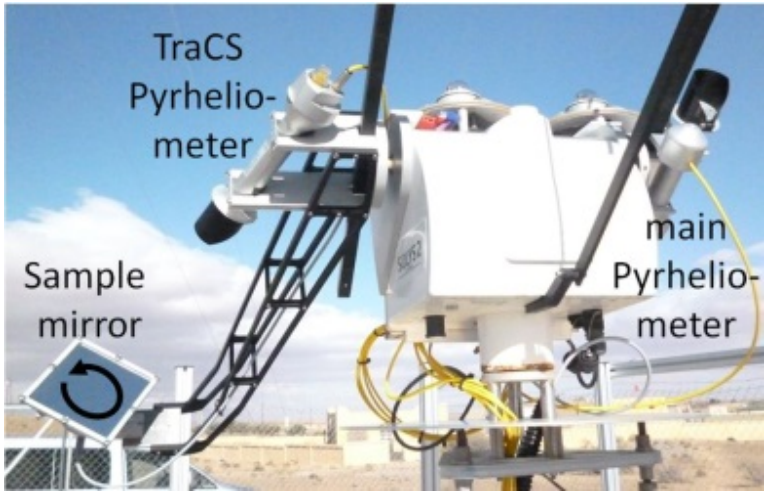
Motivation:

- A soiling model could predict the soiling rate from other weather parameters that are more broadly available
- Design model such that it can be integrated into a global dust and weather forecasting model

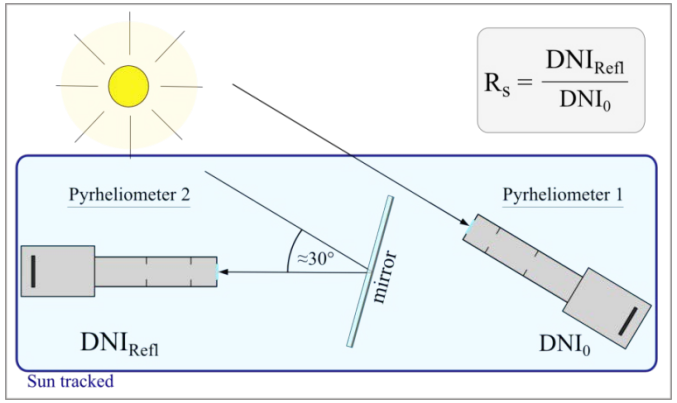
  => **soiling forecast, soiling map**

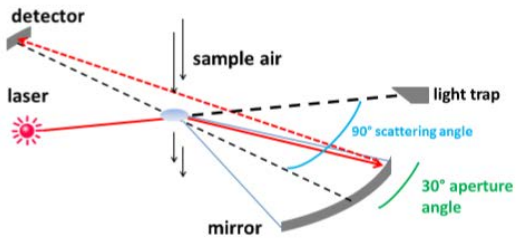
Measurement of Soiling rate

- Solar weighted specular reflectance ρ
- Cleanliness = ρ_{soiled} / ρ_{clean}
- TraCS:
  - Parallel real time measurement of 4 samples
  - Sun as light source
  - Rotation to increase measurement spot
- 5 years of CSP soiling data at PSA
- Parallel measurements of aerosol particle number size distribution (0.25 – 30 µm), wind, relative humidity, rain, dew etc.



Tracking **C**leanliness **S**ensor - TraCS





Optical particle counter

Dew sensor

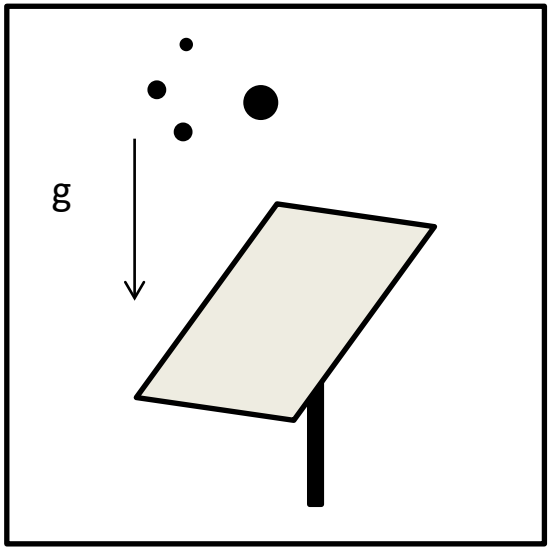
3D Wind, rain, temperature

Wolfertstetter, F., Pottler, K., Alami, A., Mezrhab, A., & Pitz-Paal, R. (2012). A novel method for automatic real-time monitoring of mirror soiling rates. SolarPACES 2012.
Wolfertstetter, F.: *Effects of soiling on concentrating solar power plants.* PhD thesis, Technische Hochschule (RWTH) Aachen, 2016

Soiling model: main deposition mechanisms

Model is based on atmospheric aerosol transport literature
Particle deposition there is characterized by the **deposition velocity** towards the ground – not a mirror!

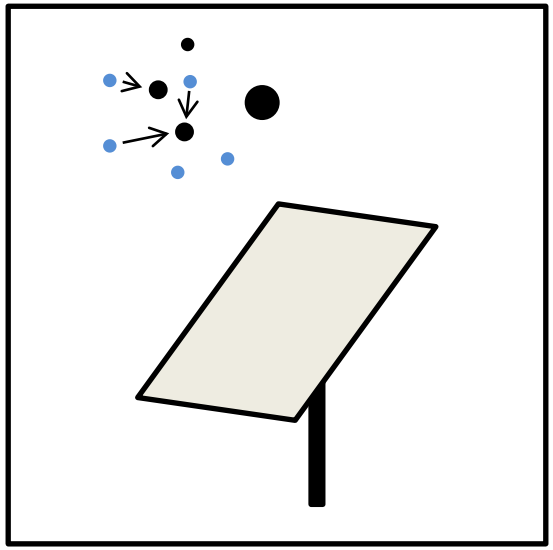
Sedimentation



➢ Gravitation

$$v_{S,p} = \frac{g\ {d_p}^2(\rho_{Aerosol} - \rho_{Luft})}{18\ \eta_{Luft}} \cdot cos(\alpha)$$

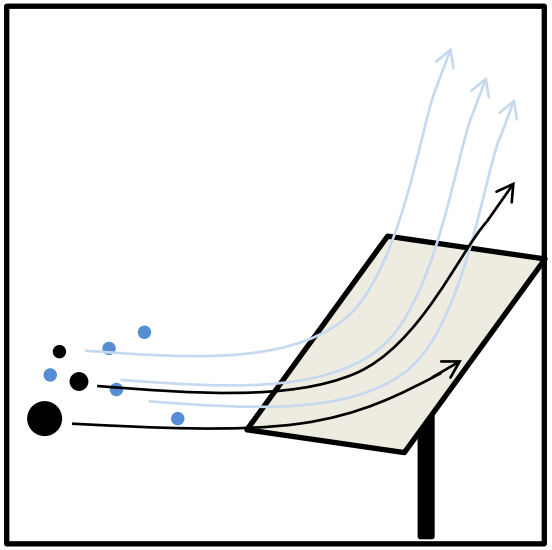
Brownian motion



➢ Thermal motion

$$v_B = a_{Brown}\ u_{Wind} \left(\frac{\nu_{Luft}}{D_B}\right)^{-\gamma}$$

Impaction



➢ Air stream/wind

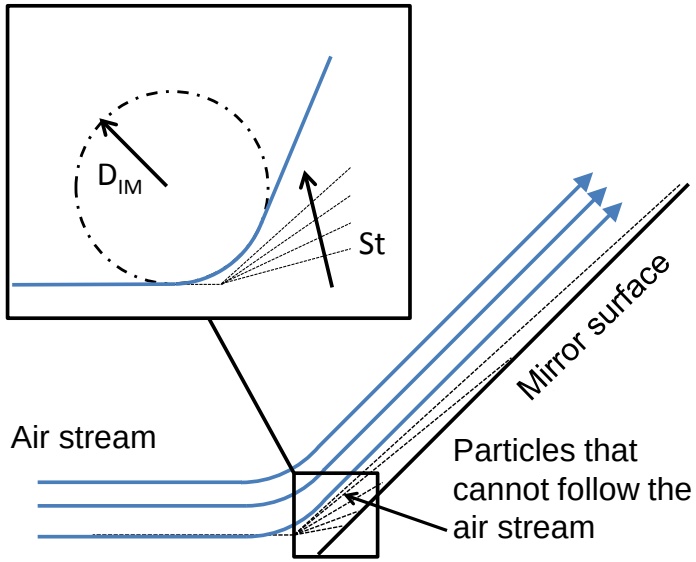
$$v_{Im} = a_{Im} \cdot \frac{\sigma_{Ausrichtung}\ u_{Wind}}{1 + \exp(-f_{Im} \cdot (St - 1))}$$

Also considered:
Rebound, resuspension, rain washing, cementation, mirror/panel orientation

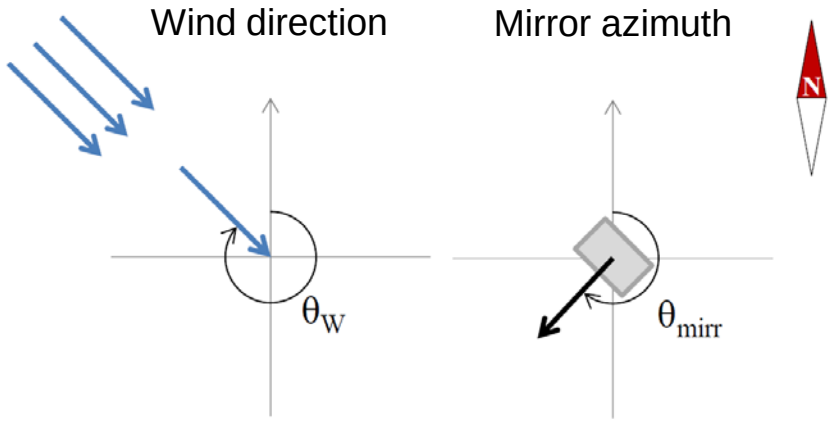
Soiling model: impaction

- Stokes number decides if particle follows the air flow (<1 = they follow)
  - D_{IM} is dependent on impact angle of air flow
- CSP mirrors are tracked

=> Mirror orientation relative to wind speed for every time step is determined to calculate deposition velocity



$$St = \frac{\rho_{Aerosol}}{18\ \eta_{Luft}} \cdot {d_p}^2 \cdot \frac{u_{Wind}}{D_{Im}}$$



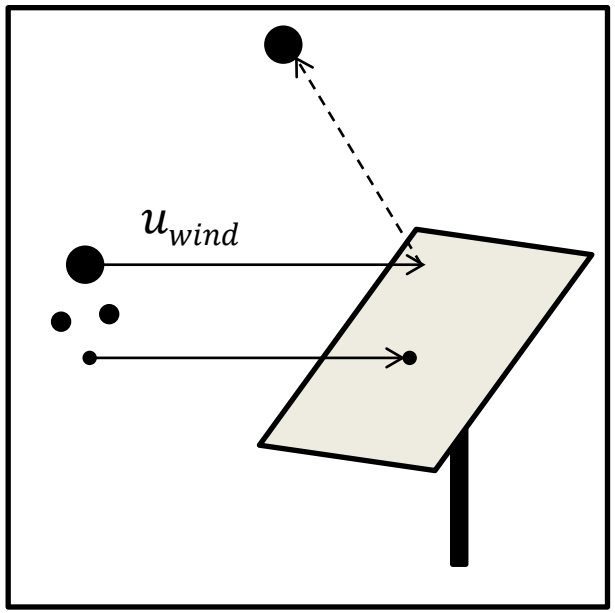
Soiling model: Particle rebound

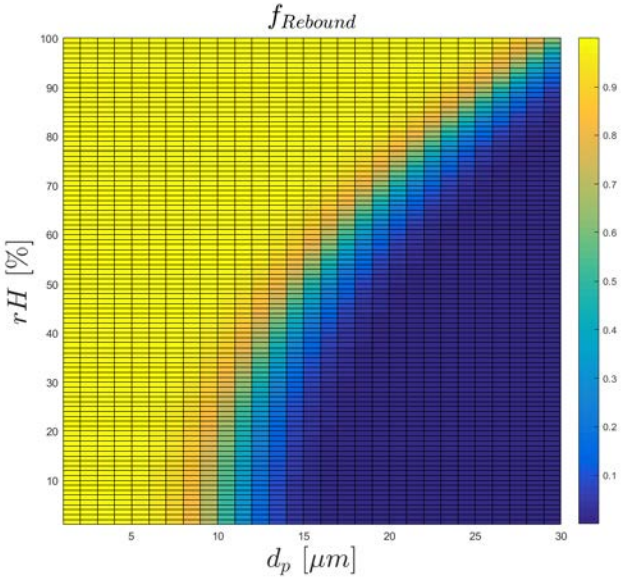
$$E_{kin} = \frac{1}{12}\ \rho_{Aerosol}\ {d_p}^3\ v_p^2 \quad > \quad E_a = \frac{A_{Hamaker}\ d_p}{12\ z_{Atom}}$$

- At wind speed u_{wind} particles bigger than threshold $d_{Rebound}$ are likely to bounce off the surface
- Described by sigmoidal:

$$f_{Rebound} = 1 - \frac{1}{1 + \exp(-f_{Reb}\ (d_p - d_{Rebound}))}$$

- Influence of relative humidity: wetness makes rebound unlikely
- Relation from data analysis





Soiling model: particle flux and surface coverage

Rate of surface coverage

Particle flux in [1/m²s]

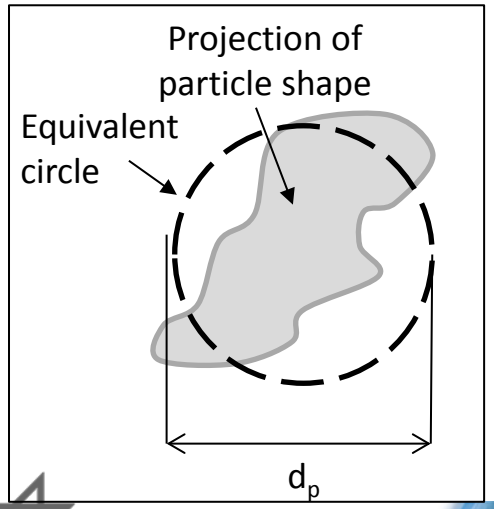
Projected surface in [m²]

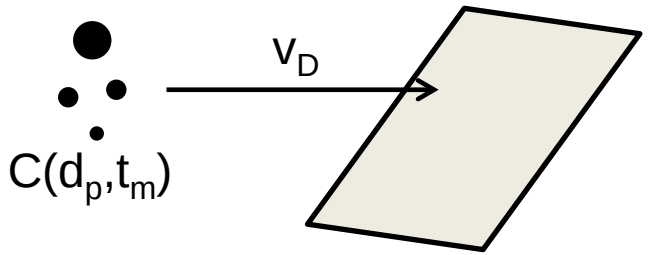
$$AR(t_m) = \sum_{d_p=0{,}25\mu m}^{32\mu m} F(d_p, u_{Wind}, \alpha_{el}, ..., t_m) \cdot {d_p}^2 \cdot \frac{\pi}{4}$$

$$= \sum_{d_p=0{,}25\mu m}^{32\mu m} v_D(d_p, u_{Wind}, \alpha_{el}, ..., t_m) \cdot C(d_p, t_m) \cdot {d_p}^2 \cdot \frac{\pi}{4}$$

From main depos process modelling

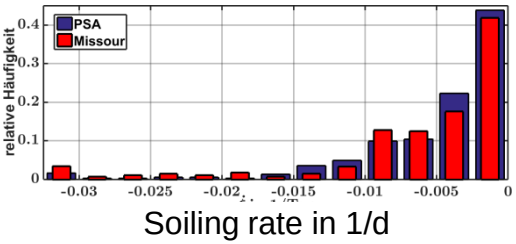
From OPC measurement



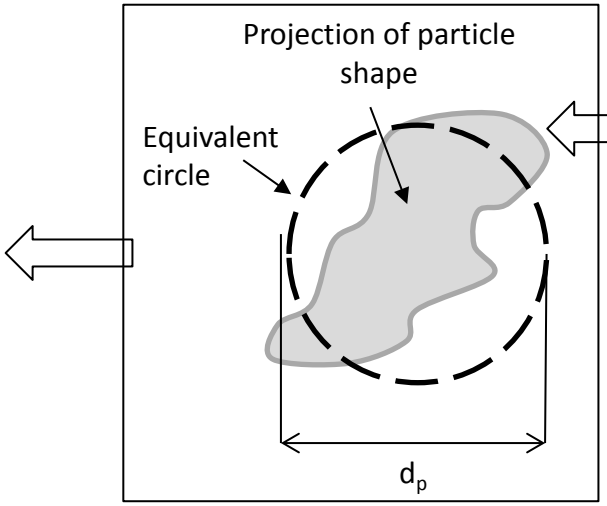


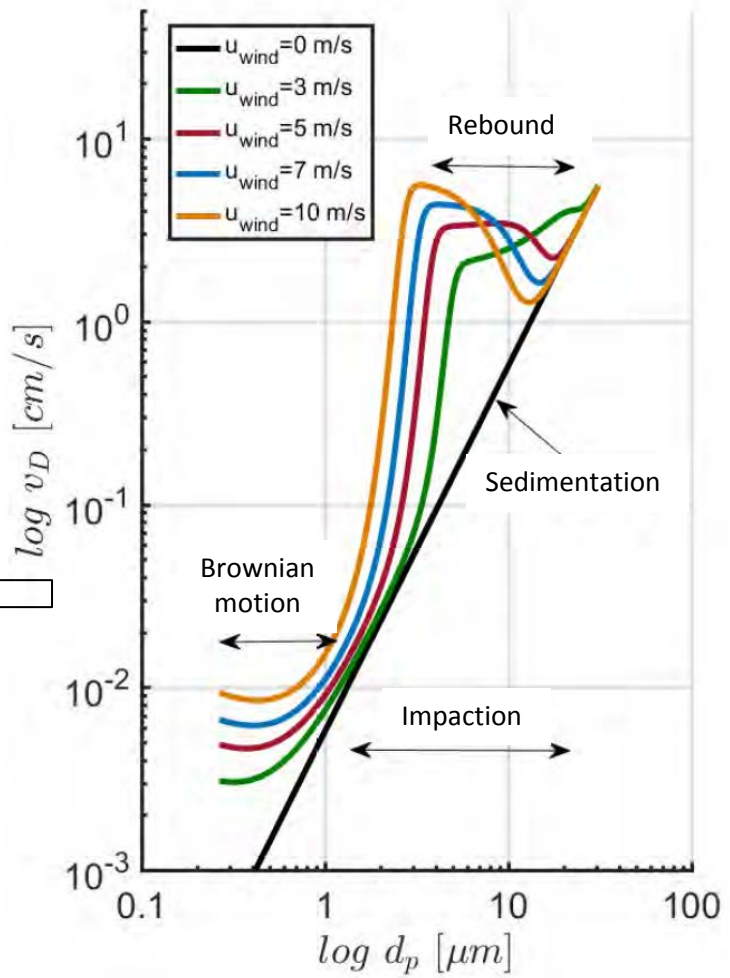
Soiling model: from depos. velocity to soiling rate

- Deposition velocity for various wind speeds agrees well with literature
- Transfer to optical effect of soiling:
  - Determine covered surface
  - Empirical linear correlation between soiling and covered surface to get soiling rate



Soiling rate in 1/d

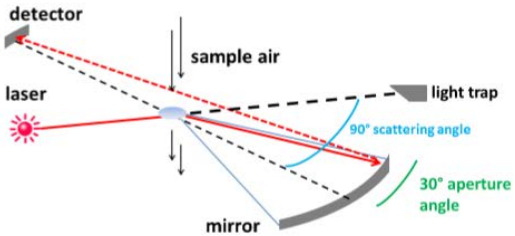


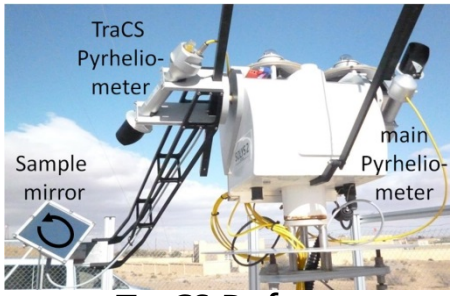


Soiling model: input data and parameterization

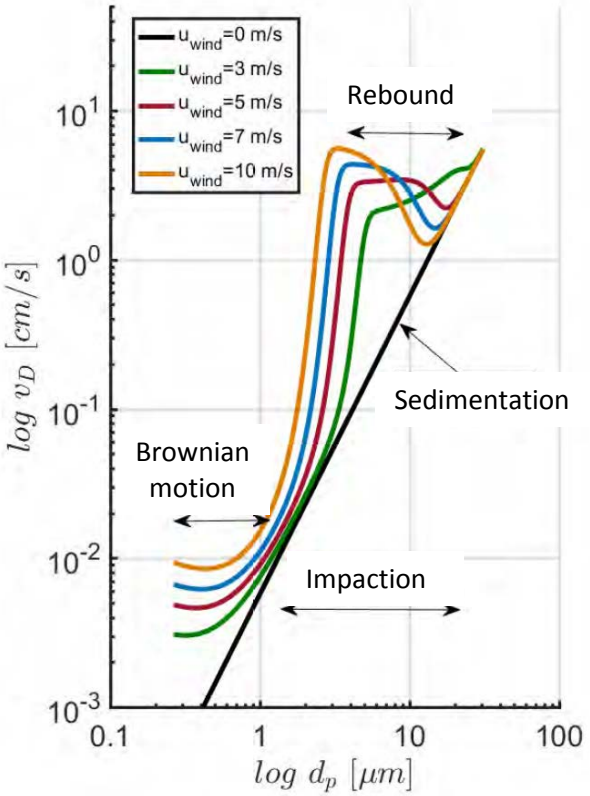
- 8 unknown model parameters
- **Fitted by parameterization** with one part of the measurement dataset
  - Aerosol particle number concentration from 0.25 µm - 30 µm
  - Wind, relative Humidity, rain, irradiance, dew, temperature, etc.
- Second part of data used for **model validation**

Optical particle counter





TraCS Reference



Measure-ment sites

Dew sensor

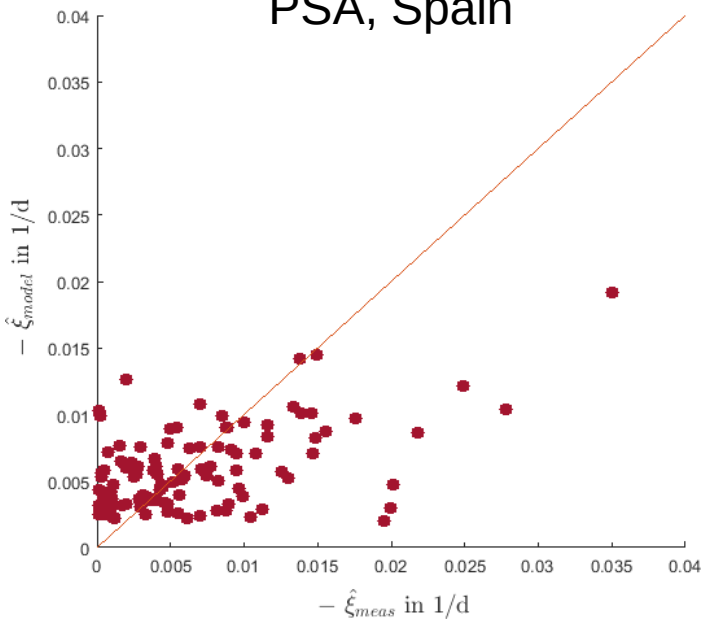
3D Wind, rain, temperature

Soiling model performance

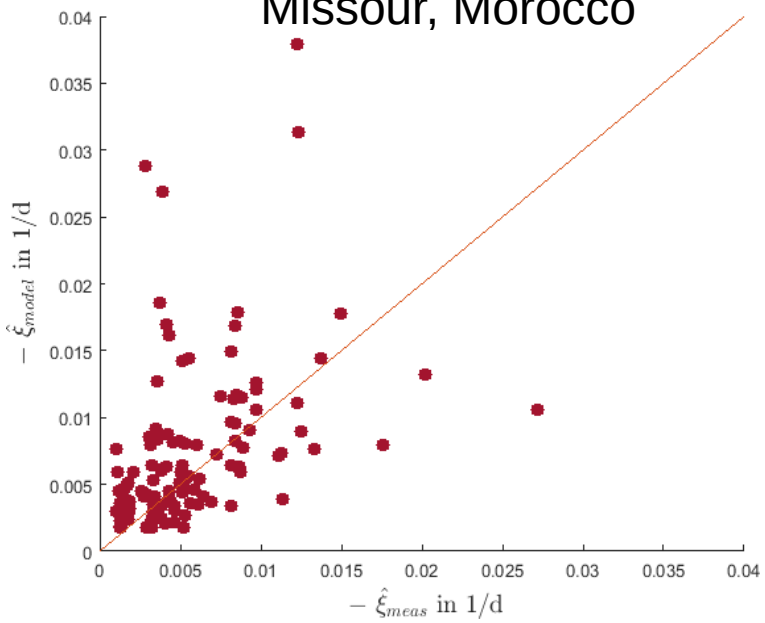
	Bias ($\cdot\ \%/d$)	RMSE ($\%/d$)
PSA Training Set	0.08	0.43
PSA Test Set	0.11	0.44
Missour	0.09	0.46

- Model validated for **two sites**
- RMSE = 2 x soiling rate measurement accuracy
- Bias = 0.5 x soiling rate measurement accuracy

PSA, Spain



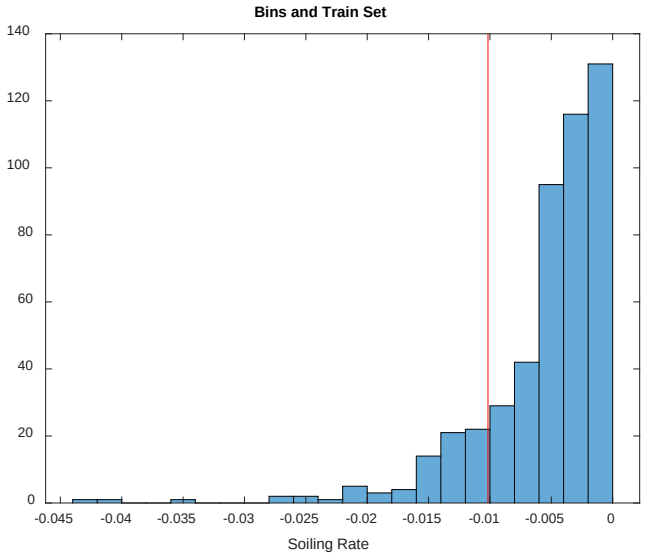
Missour, Morocco

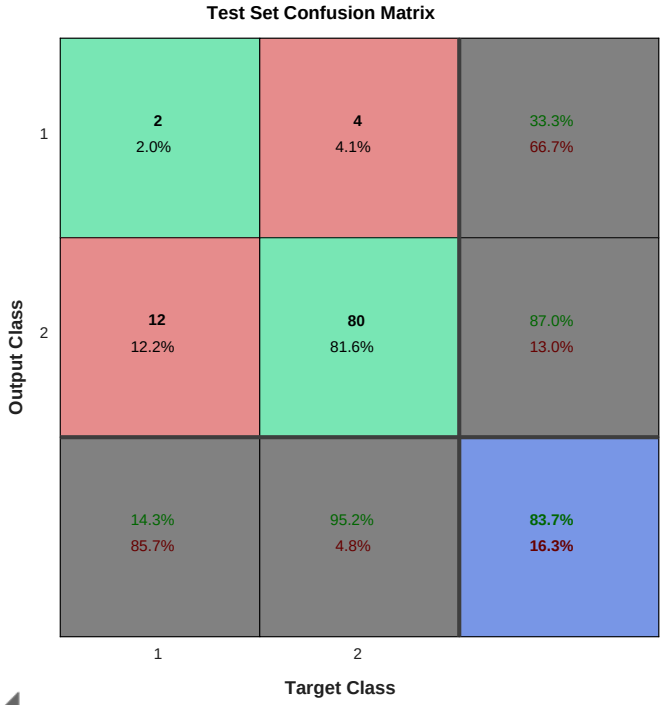


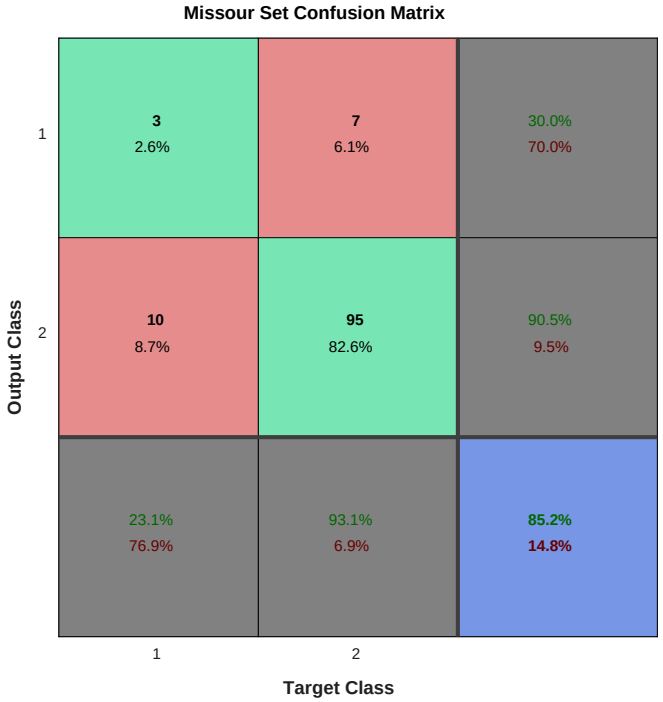
Soiling and condensation model applied to CSP solar field – DLR Report, WASCOP H2020 project D3.2, 2018, to be published online on www.wascop.eu,

Soiling model performance

- **Approximate soiling** information is often sufficient for cleaning scheduling
- Binning of soiling rate into low (<1 %/d) and high (>1 %/d) soiling rate
- Result: low soiling days are predicted correctly with more than 90% probability



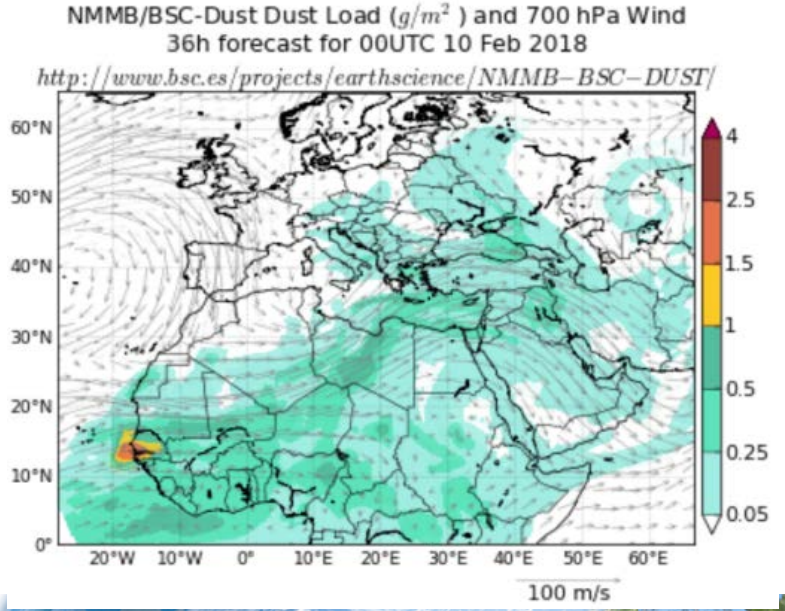




Outlook: Soiling rate map and forecast

- Atmospheric **dust transport model** NMMB MONARCH by BSC:
  - Based on weather forecasting models
  - 36h (regional) – 72h (global) forecast of atmospheric dust load and „deposition“ in 10 x 10 km^2 resolution
  - The model includes the weather parameters used in our soiling model

=> It is possible to integrate the CSP soiling model into dust transport models



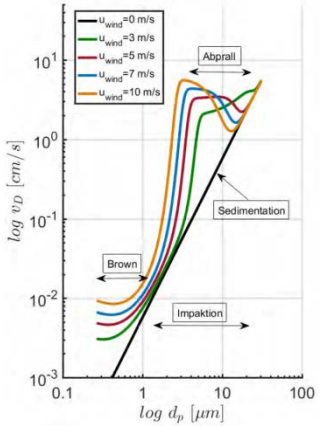
https://dust.aemet.es/forecast

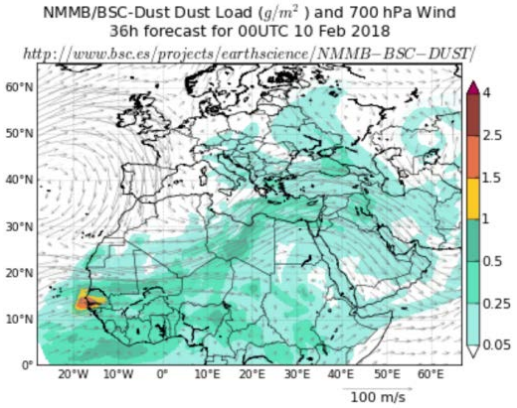
Outlook: Soiling rate map and forecast

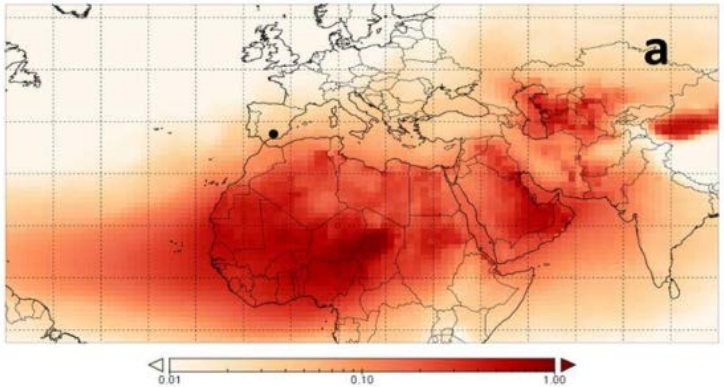
Activities within the SOLWATT project in collaboration with BSC:

- integrate the CSP soiling model into BSC atmospheric dust transport model
- Expected outcomes:
  - soiling rate forecast for the next 36 hours
  - soiling rate map from reanalysis of historical dust model data

- Aplication to absorber tube and PV soiling is possible (not foreseen in SOLWATT)







Conclusions and outlook

- Extensive soiling and weather measurement dataset has been acquired at two sites
- Soiling model has been developed based on deposition mechanisms
- Model is optimized with training dataset from PSA
- Validation for data from two sites delivers promising results
- Integration into dust forecast model is foreseen to create soiling forecast and soiling map

Thank you for your attention

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Recommended reference on soiling model:
http://wascop.eu/wp-content/uploads/2018/06/WASCOP_deliverable_3.2_final_plainText.pdf

DLR

References

[W4] **Wolfertstetter et al, „Soiling and Condensation model applied to CSP solar field“, WASCOP project report 3.2, 2018, http://wascop.eu/wp-content/uploads/2018/06/WASCOP_deliverable_3.2_final_plainText.pdf**

[Wi] **Wilbert**, S.: *Determination of Circumsolar Radiation and its Effect on Concentrating Solar Power.* PhD thesis, Technische Hochschule Aachen, 2014.

[W1] **Wolfertstetter**, F.*: Effects of soiling on concentrating solar power plants.* PhD thesis, Technische Hochschule (RWTH) Aachen, 2016

[K] **Knisely**, B., S. V. **Janakeeraman**, J. **Kuitche** . G. TamizhMani: *Validation of Draft International Electrotechnical Commission 61853-2 Standard: Angle of Incidence Effect on Photovoltaic Modules.* Arizona State University, Photovoltaic Reliability Laboratory, 2013.

[L] **Laven**, P.: *MiePlot - A computer program for scattering of light from a sphere using Mie theory & the Debye series.* Computer Program, 2017.

[Wa] **Wagner**, R., T. **Ajtai**, K. **Kandler**, K. Lieke, C. Linke, T. Müller, M. Schnaiter . M. Vragel: *Complex refractive indices of Saharan dust samples at visible and near UV wavelengths: a laboratory study. A*tmospheric Chemistry and Physics, 12(5):2491–2512, mar 2012.

[F] **Figgis**, B.: *PV Soiling: Qatar Perspective.* DEWA Soilingworkshop 2016*, 2016*

[T] THERMVOLT Systemvergleich von solarthermischen und photovoltaischen Kraftwerken für die Versorgungssicherheit Schlussbericht 01.11.2014 - 30.06.2016

[B] Bellmann, P., Oct. 2017, „**Investigation of soiling on mirror and glass samples with regard to power losses in CSP and PV technologies**“, Diploma thesis, University of Dresden

[Sc] Schüler, David, et al. "The enerMENA meteorological network–Solar radiation measurements in the MENA region." AIP Conference Proceedings. Vol. 1734. No. 1. AIP Publishing, 2016.

[W2] Wolfertstetter F, Wilbert S, Dersch J, Dieckmann S, Pitz-Paal R, Ghennioui A. Integration of Soiling-Rate Measurements and Cleaning Strategies in Yield Analysis of Parabolic Trough Plants. ASME. J. Sol. Energy Eng. 2018

[W3] Wolfertstetter, F., Pottler, K., Alami, A., Mezrhab, A., & Pitz-Paal, R. (2012). A novel method for automatic real-time monitoring of mirror soiling rates. SolarPACES 2012.

[FG] A. Fernández-García, F. Sutter, L. Martínez-Arcos, C. Sansom, F. Wolfertstetter, C. Delord, Equipment and methods for measuring reflectance of concentrating solar reflector materials, Solar Energy Materials and Solar Cells, Volume 167, 2017

[S] Schüler, David, et al. "The enerMENA meteorological network–Solar radiation measurements in the MENA region." AIP Conference Proceedings. Vol. 1734. No. 1. AIP Publishing, 2016.

Soiling measurement setup at PSA

PV reference cells

PV panels SCC comparison

TraCS for 4 mirrors

transmission measurement (tubes)

PV panels

TraCS for 4 mirrors

rain

Optical particle counter

visibility

wind

[S], https://www.dlr.de/sf/en/desktopdefault.aspx/tabid-8680/12865_read-32404/

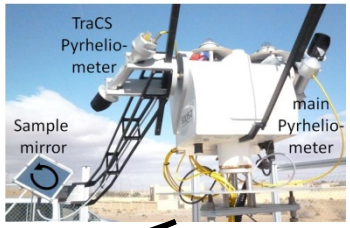
enerMENA network

Operational since 2010 -2013

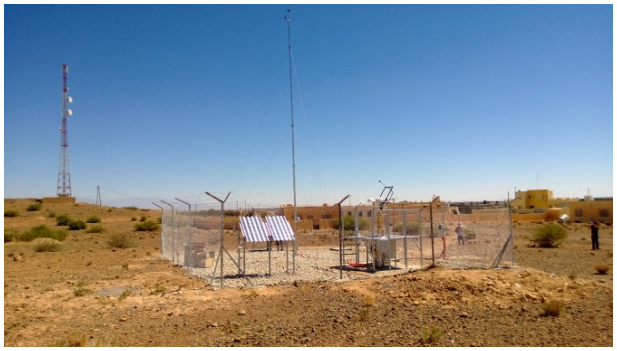
12 meteorological measurement stations (solar irradiance, temperature, pressure, relative humidity, wind, etc…)

Scatterometer FS11from Vaisala

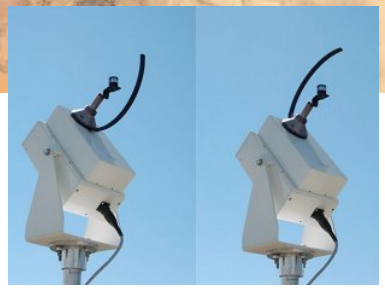
Grimm EDM164 Particle counter



TraCS for mirrror soiling

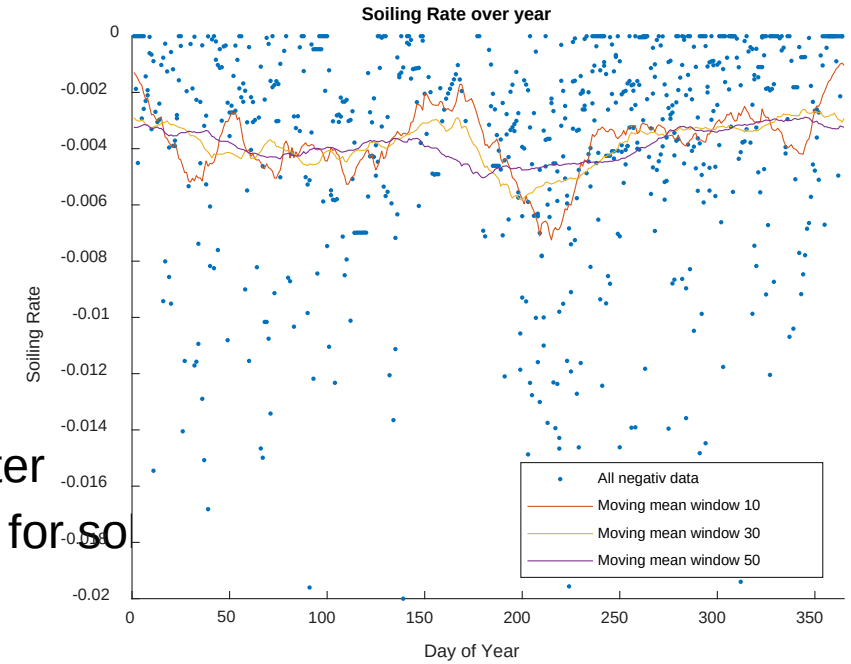


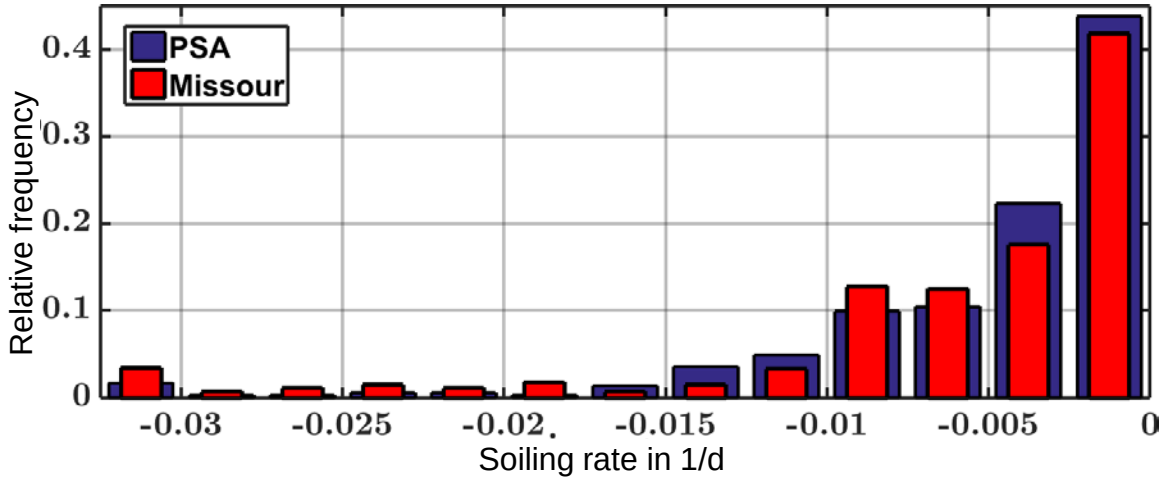
HVS-TSP16 from MCZ: gravimetric measurement principle



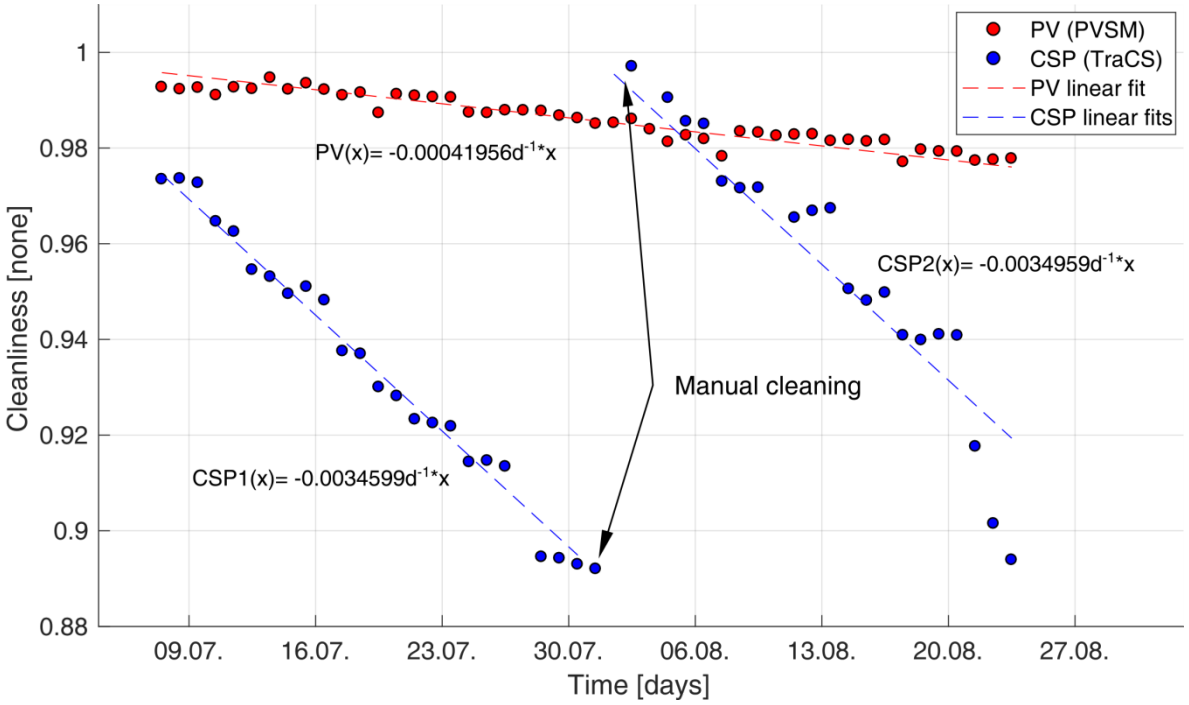
Soiling rate

- Soiling rate = reduction of cleanliness over time
- Soiling rate is dependent on time and location
- Not (yet) a standard measurement parameter
- Little information available in target regions for so





Comparison of soiling



→ CSP soiling rate approx. **8-9 times higher** than PV (0.35%/d and 0.04%/d)

→ Assumption: same surface densities of dust and dirt